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A field-oriented competition index for young jack pine plantations and a computerized decision tool for vegetation management

D. M. MORRIS and R. R. FORSLUND

Ontario Ministry of Natural Resources, Ontario Forest Research Institute, Centre for Northern Forest Ecosystem Research, c/o Lakehead University, Thunder Bay, Ontario, Canada, P7B 5E1

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Application. A field-oriented competition index and accompanying software for a hand-held microprocessor have been developed for on-site evaluation of young jack pine plantations. This index has the potential to be used to set tending priorities, or when used in a pre- and post-herbicide assessment, to determine the effectiveness of various release treatments.

Abstract. A field-oriented competition index (Shade Index) was developed using a series of mensurational measurements on competitors surrounding individual jack pine seedlings. This index and accompanying software were developed for a hand-held microprocessor, allowing for on-site evaluations.

The Shade Index estimates the percent occupancy of competitor crowns overtopping individual jack pine seedlings within a 1.4 m radius of the subject tree. Using 360 crop tree-centred plots situated on six four-year-old plantations, the accuracy of the index was tested against a more complex competition index (Total Canopy Cover) obtained from vertical hemispherical photographs. Both of these indices attempt to quantify the amount of light being intercepted by competitors. A relationship was found to exist between these two indices with Pearson correlation coefficients ranging from 0.82 to 0.90. Linear regression models of seedling diameter regressed against the Shade Index for the different site/stock type combinations are presented. All models were significant at greater than $p = 0.0001$, with coefficients of determination ranging from 0.42 to 0.71.

This index was incorporated into software for a hand-held microprocessor to allow on-site evaluation. These evaluations have the potential to be used to set tending priorities or assess vegetation control measures.

Introduction

Jack pine (*Pinus banksiana* Lamb.) is the second most important species

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harvested in Ontario, Canada, constituting 27.6% of the total provincial cut (Anonymous 1990). Presently, 60% of the land artificially regenerated annually in Ontario is either seeded or planted to jack pine (Anonymous 1987). Jack pine can grow on a wide variety of soil types (Fowells 1965) and is considered one of the fastest growing boreal conifers during the first twenty years (Kabzems and Kirby 1956). Unfortunately, the shade-intolerant nature of jack pine (Hosie 1979) poses a serious establishment threat on those sites with severe competition from perennial vegetation. The rich boreal mixedwood sites, which comprise 45% to 50% of Ontario's forested land (McClain 1981), contain a large component of fast-growing hardwoods developed primarily from root suckers after harvest. The dynamic nature of these sites demands rapid tending decisions to reduce competitive growth losses to jack pine and to avoid the need for costly refill planting (Tappeiner and Wagner 1987). Traditionally, these tending decisions are based solely on qualitative assessments of plantation performance, rather than on quantitative measurements based on sound biological relationships between competition and crop tree growth response. These qualitative assessments could result in regeneration failures as well as the mismanagement of limited tending dollars through incorrect ranking of tending priorities.

Considerable work has identified light as the most important environmental factor influencing early seedling performance for shade intolerant species (Reed et al. 1983; Brand 1986; MacDonald et al. 1990). It should be recognized that indices that quantify light interception may not be appropriate on sites dominated by low-statured competitors (e.g., grass, raspberry) or on sites where moisture stress may be a limiting factor. In order to quantify the percent light intercepted by the developing hardwood canopy, Morris and MacDonald (1991) used total canopy cover derived from vertical hemispherical photographs taken at the base of seedling leaders. The authors determined that this light index provided an accurate estimate of the perennial woody competition on a given site and demonstrated a linear relationship between total canopy cover and seedling root collar diameter four years after outplanting. Although specific questions regarding the sensitivity to competition of the various species and stock types outplanted in Northern Ontario were addressed, the application of hemispherical photography to evaluate plantation performance on an operational basis is not practical. Extensive laboratory time is necessary to process film, delineate the canopy cover, determine the canopy area, and calculate the corresponding index value. The use of automated measurement systems, based on the opacity of the corresponding negatives (Bonhomme and Chartier 1972; Olsson et al. 1982; Chan et al. 1986), may substantially decrease laboratory time, but such systems cannot replace on-site evaluations.

The availability of hand-held microprocessors now makes on-site evaluations possible without incurring additional keypunching and analysis costs (Scale 1989) which provide the potential to eliminate the automated analysis of hemispherical photographs. Brand (1988) describes a pilot plantation assessment system developed for a portable datalogger. This system uses a series of support programs to project free-to-grow status, evaluate stocking and spatial distribution of seedlings, and by linking to a Geographic Information System (GIS) provides a detailed map of the results.

The first objective of this study was to use mensurational measurements taken on competitors surrounding individual jack pine seedlings to develop a field-oriented competition index which approximates the index obtained from vertical hemispherical photographs. The second objective was to develop a computer program for a hand-held microprocessor as a tool for making on-site tending decisions based on a quantitative assessment of the competing vegetation. This program could be included in a plantation assessment system as described by Brand (1988).

Methods and materials

Data collection

The data used in this study were collected in 1988 from six four-year-old jack pine plantations. Three of the plantations were established with overwintered containerized stock and three with 2 + 0 bare root stock. These plantations were located in northwestern Ontario, within a 150 km radius of Thunder Bay, Ontario, between 48°09′N and 49°36′N latitude and between 90°09′W and 92°15′W longitude. The sites selected covered a range of soil textures for both stock types. On the sites studied, a wide assortment of perennial shrubs and tree species developed primarily from root suckers after harvest. The tree stratum was dominated by trembling aspen (*Populus tremuloides* Michx.) and white birch (*Betula papyrifera* Marsh.), with the shrub stratum consisting primarily of beaked hazel (*Corylus cornuta* Marsh.), speckled alder (*Alnus rugosa* (Du Roi) Spreng.), mountain maple (*Acer spicatum* Lam.), and willow (*Salix* spp.). A total of 360 crop tree-centered plots (60 per plantation) was used in this study.

Two approaches to measuring the competition surrounding the subject tree were employed. In the first approach, a vertical hemispherical photograph was obtained in mid-July using a 7.5 mm equidistant fisheye lens. In this region, jack pine shoot growth has been known to continue into late August (Fowells 1965). This can be further complicated by lammas

growth. To account for this variability, the fisheye lens was levelled with the camera focal plane at the base of each jack pine seedling's leader.

In the second approach, a series of mensurational measurements were taken on all perennial competitors taller than the seedling height at the base of its current leader (camera location for hemispherical photograph) which were located within a 1.4 m radius of each subject tree. It was determined that on these sites, this radius would include those competitors which contribute most of the competitive effect (MacDonald et al. 1990). The measurements taken for each competitor included:

1) horizontal distance from the competitor's crown centre to seedling (D);
2) azimuth from seedling (AZ);
3) average crown width (CW) determined from two measures of crown width taken perpendicular to each other; and
4) crown density as an estimated percent of total crown volume occupied by foliage (CD).

Total seedling biomass and root collar diameter have been found to respond to changing levels of competition (Zutter et al. 1986; Morris et al. 1990). The simplicity of using root collar diameter, combined with the avoidance of destructive sampling, make the incorporation of this input variable desirable for on-site evaluations of plantation performance on an operational level. Therefore, root collar diameter (mm) was measured for each of the sampled seedlings and used as the growth response variable in the analysis. Naturally regenerated seedlings (eleven in total) were eliminated from the analysis.

A 300 g soil sample was taken from the upper B-horizon near the base of each seedling sampled. In the laboratory, the soil samples were air-dried, sieved (2 mm), and analyzed for sand, silt, and clay fractions (Bouyoucos hydrometer method).

Formulation of competition indices

The percent areas of open sky and opaque canopy were determined from hemispherical photographs. The remaining area between the two extreme light regimes was classified as transparent canopy. This area represented a combination of small open sky areas and larger opaque regions. During preliminary testing, Morris et al. (1990) determined that the transparent canopy blocked approximately two-thirds of the potential radiation intercepted by the canopy. Total Canopy Cover was, therefore, calculated using Eq. (1):

$$\text{Total Canopy Cover} = \text{Opaque \%} + (\text{Transparent \%} \times 2/3). \quad (1)$$

Using the mensurational competitor data collected for each crop tree-centered plot, a series of computations was carried out to determine a competition index (Shade Index). The angle θ (Fig. 1a) subtended by each competitor was calculated using the relationship:

$$\theta = 2 \sin^{-1} [(CW/2)/D]. \quad (2)$$

The calculation of the angle θ incorporates both distance- and size-weighted factors used in many neighbourhood indices (Rejmanek and Messina 1989). If the competitor was growing alone (e.g., no other competitor crowns overlap it), this angle was used to determine the total wedge area (TWA_i). If crown overlap occurred, the extreme outside angles of the group were used forming one large crown wedge. Once θ was determined, the total wedge area was calculated by determining its fraction of the circular plot area with radius ($R = 1.40$ m) as follows:

$$TWA_i = \pi \times R^2 \times (\theta/360). \quad (3)$$

The front wedge area (FWA_i) between the competitor's crown edge and the centre of the subject tree crown was determined similarly to TWA_i by replacing the plot radius (R) with the distance to the closest competitor's crown ($D - CW/2$) in Eq. (3). The Shade Index was then calculated as follows:

$$\text{Shade Index} = \left(\sum_{i=1}^{n} (TWA_i - FWA_i) \right) \Big/ \text{Plot Area}. \quad (4)$$

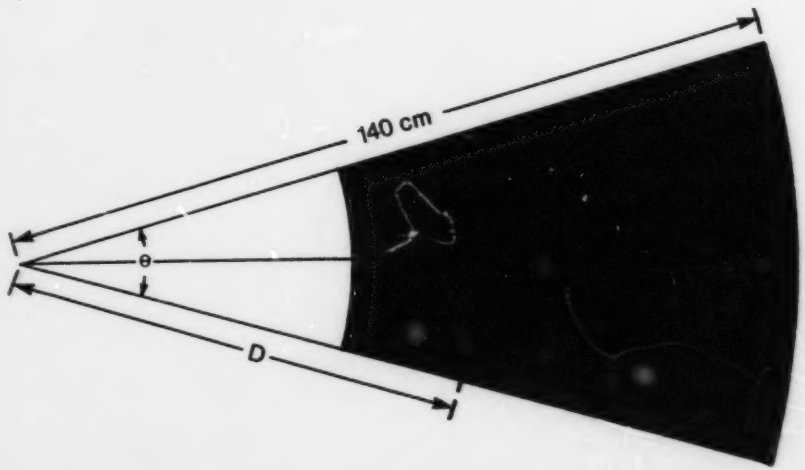

Fig. 1a. An example illustrating the trigonometric computations carried out to determine the areas of the competition wedges.

The plot area is a constant equal to 6.158 m^2. In Fig. 1a, the shaded area represents the opaque area for wedge$_i$ which is simply the subtraction of FWA_i from TWA_i. In the example presented in Fig. 1b, the opaque areas for each of the four competition wedges are summed (1.6 m^2) and divided by the plot area (6.158 m^2) to obtain a Shade Index of 0.2594 or 25.94%.

A problem arises when a competitor's crown overlaps the subject tree and the angle θ cannot be determined. Also, overestimates of θ can occur when small competitor crowns are located extremely close to the plot centre. To avoid both of these situations, any competitor crown within a 30 cm radius of the plot centre was moved outward so D = (CW/2) + 30. Trials using a radius ranging from 5 cm to 60 cm (5 cm increments) were conducted. It was determined that by using a 30 cm radius the majority of the index values were not altered, or only altered slightly. However, the influence of those values identified as outliers on the original scatterplots was reduced using this modification.

While developing any competition index, numerous alternatives exist. These alternatives can range from simple, one-variable indices to indices involving complex, multi-variable computations. Such was the case while developing the Shade Index. One-variable indices (e.g., competitor density and competitor crown area sums) were tested using regression analysis, but were found to relate poorly to seedling diameter growth. Complex indices incorporating competitor heights and crown lengths (e.g., vertical angles sums, crown volume sums) were also tested. Using the crown

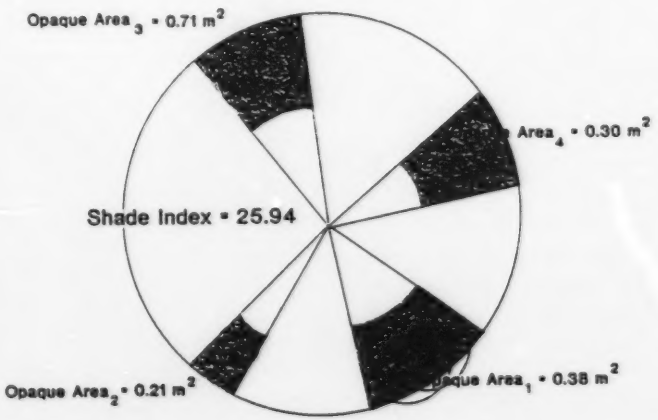

Fig. 1b. An illustration of a two dimensional canopy map used to determine the Shade Index in the program CANOPY.GBA.

density measurement in addition to average crown width, azimuth, and competitor distance, an index was developed which included an estimate of diffuse light penetrating through the competitor crowns. This index was further complicated by including competitor height and crown length data which were used to develop a three-dimensional representation of the canopy structure. It is noteworthy that the computation of these complex indices substantially increased calculation time and more importantly, they did not provide an improvement in explaining the variation in seedling diameter over the index outlined in Eq. (4). Previous authors (Daniels 1976; Lorimer 1983; MacDonald et al. 1990) have also found that complex measures are largely unjustified. Many of the indices evaluated relied on a subjective measurement of crown density. Although other authors have demonstrated that percent cover (subjective) can be an effective measure of competition (Brand 1986; Wagner and Radosevich 1987; Simard 1990), the application into an operational context may be difficult. Although these measurements are rapid, errors in judgement made by field personnel caused by a varying degree of experience could limit their effectiveness. Therefore the Shade Index was retained.

Statistical analysis

Pearson product-moment correlation coefficient in simple correlation analysis was used to test the degree of association between Total Canopy Cover (Eq. (1)) and the Shade Index (Eq. (4)) for each plantation studied.

Using linear regression, seedling root collar diameter was used as the dependent variable and was regressed on the Shade Index. The resulting regression equations for each stock type/site type combination were then used in the on-site plantation evaluation software described below.

Plantation evaluation software

To quantify tending decisions in the field, a computer program (CANOPY.GBA) was written in GWBASIC for use on a hand-held microprocessor. In this study we used a Microflex PC-9000. The program accepts input of site, stock type, and competitor data, calculates a Shade Index using Eqs (2) through (4), asks for a maximum allowable growth reduction limit, and responds with a tending decision (Yes/No). This decision is based on the critical (threshold) competition index level determined from the intersection of the appropriate regression line (specified by site and stock type inputs) and the maximum allowable growth reduction limit. All input data and subsequent calculations are saved in a

data file for later reference. Copies of the program are available upon request.

Results and discussion

Comparison of indices

The results of the simple correlation analysis indicated that a linear relationship existed between Total Canopy Cover and the computer-generated Shade Index (Table 1: $r = 0.82$ to 0.90). All correlation coefficients were significant at levels greater than $p = 0.0001$, therefore it is reasonable to assume that the Shade Index represents a close approximation of Total Canopy Cover.

Relationship of indices to seedling diameter

Figure 2 presents a series of scatterplots depicting the relationship between the Shade Index and seedling root collar diameter for the six plantations studied. Although a linear relationship can be observed in these scatterplots (linear regression lines and 95% confidence intervals are included on the scatterplots), a slight clustering of points at high levels of competition does occur. This clustering may be caused by the Shade

Table 1. Site and stand characteristics for the six plantations studied.

Plantation number	Stock type	Soil texture		Competitor density[1] stems/ha	Non-crop Canopy composition		Correlation coefficient[2]
		sand %	clay %		Tree %	Shrub %	
1	cont.	31.1	36.0	52,425	80.3	19.7	0.832
2	cont.	49.5	20.9	21,300	56.2	43.8	0.896
3	cont.	59.2	16.9	40,489	26.1	73.9	0.900
4	2+0	52.6	21.1	19,676	48.6	51.4	0.900
5	2+0	58.6	19.9	18,323	71.6	28.4	0.892
6	2+0	53.6	20.9	16,645	88.3	11.7	0.820

[1] Densities are based on competitor counts (only competitors greater than height to base of seedling leaders) from 60 subplots (area = 6.2 m^2) per plantation.

[2] Pearson correlation coefficients are between the computer-generated Shade Index and Total Canopy Cover ($n = 60$ for each plantation).

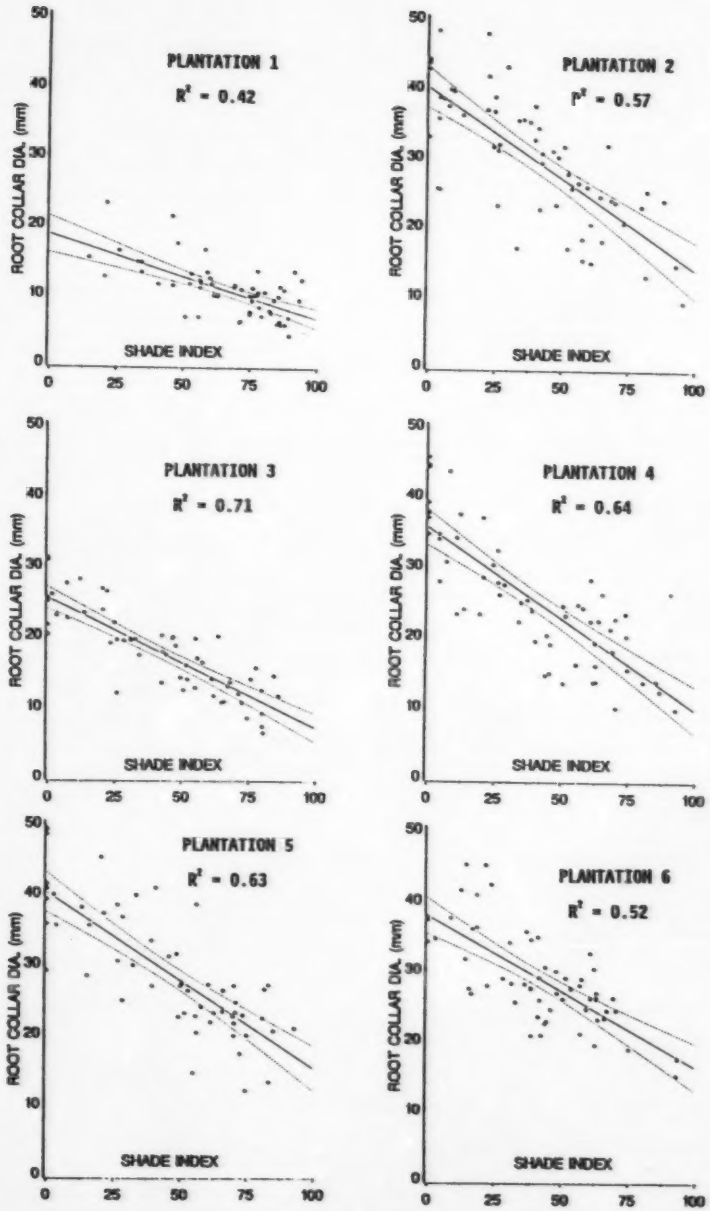

Fig. 2. Scatterplots, linear regression lines, and 95 % confidence limits for six plantations studied depicting the relationship between seedling root collar diameter and the Shade Index.

Index's inability to account for the three-dimensional architecture of the developing canopy. Vertical gaps between overlapping crowns are not detected in a two-dimensional approach as used in the computation of the Shade Index. At low competition levels, little or no overlap of competitor crowns occurs, and the index provides a similar estimate of solar blockage to that determined by the hemispherical photographs. However, as the amount of overlap increases, the Shade Index increasingly overestimates the opaque canopy fraction and reaches its maximum, even though the seedlings are still receiving some light. It was felt that the increased variation in seedling growth caused by this limitation of the two-dimensional approach was minor, and therefore transformations or non-linear regression techniques were not employed.

Table 2 presents a summary of the results of seedling diameter regressed against the Shade Index for the six areas studied (MSE, *F*-ratios, R^2, y-intercept, and slope). It should be noted that all linear regression models were significant at probabilities greater than $p = 0.0001$. The species composition of the competitors, in part, influenced the strength of the relationship between the Shade Index and seedling diameter. Slightly lower coefficients of determination occurred for Plantations 1 and 6 (Table 2). The canopies on these plantations were comprised of a greater ratio of tree species (greater than 80% — Table 1). The vertical development of tree crowns is different than that of shrub species. Tree crowns tend to represent only the upper 50% of the total height of the tree and are asymmetrical, whereas shrub crowns commonly comprise over 90% of the height with more uniform shape and distribution of leaf area. Open areas under and through the crown of a "tree" competitor, undetected by

Table 2. Linear regression results[1] for seedling diameter regressed against the Shade Index.

Plantation number	Soil texture	Sample size	Shade Index				
			MSE	F-ratio	R^2	B_0	B_1
Container stock:							
1	fine	58	8.38	40.10	0.42	18.74	−0.121
2	medium	59	38.09	74.19	0.57	40.10	−0.262
3	coarse	58	10.32	137.32	0.71	25.47	−0.183
Bare root stock:							
4	fine	59	30.06	101.70	0.64	35.49	−0.257
5	medium	56	28.82	92.34	0.63	40.32	−0.250
6	coarse	59	21.78	62.85	0.52	37.96	−0.217

[1] Regression model was $y = B_0 + B_1x$, where y = seedling root collar diameter (mm) and x = shade index. All linear regression models were significant at greater than $p = 0.0001$.

the Shade Index, may provide a significant portion of the total radiation to an individual seedling. These open areas are uncommon in canopies dominated by shrub species.

Silvicultural considerations of evaluation software

As previously outlined, CANOPY.GBA prompts the user with the following questions prior to measurement (all responses must be numeric): 1) site type code, 2) stock type code, and 3) maximum allowable growth reduction (%). The program then proceeds to prompt the user for mensurational data of competitors (distance, azimuth, and two measures of crown width). After each competitor is measured, the user is asked if there are more competitors on the plot. Once a "no" response is entered, the program asks if another plot will be measured. After the desired number of plots have been tallied, CANOPY.GBA computes the mean Shade Index for the plantation.

Figure 3 illustrates how CANOPY.GBA makes its tending decision. The regression line for bare root jack pine seedlings planted on medium textured soils was used in this example. A critical (threshold) Shade Index value is determined as the point of intersection between the growth response curve (regression line) and the maximum allowable growth reduction line (horizontal line). In this example, with the maximum allow-

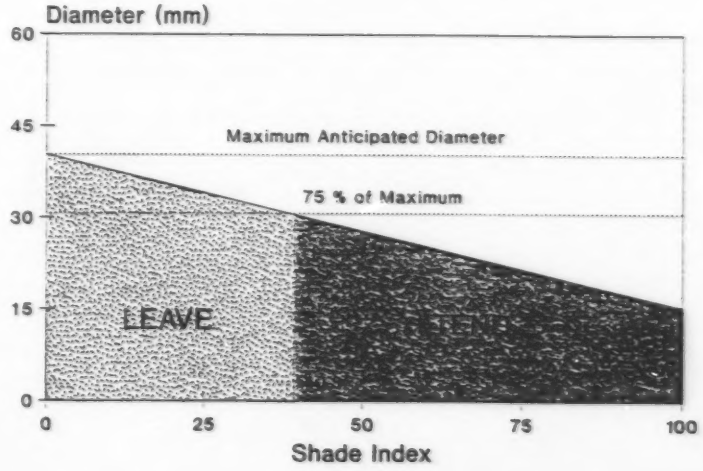

Fig. 3. An example illustrating the rationale for the tending decision made in the program CANOPY.GBA.

able growth reduction set at 25% (75% of maximum potential), any plantation with a mean Shade Index value greater than 40.3 would require tending. This maximum allowable growth reduction limit is user-specified, but would be determined at the forest management policy level for a given region. This kind of decision is extremely complex and is based on a host of interrelated factors. Some factors to be considered include: management objectives, treatment options, cost of prescribed treatment versus total tending budget, treatment effects, and the economics of enhanced stand growth compared to regional wood supplies. These factors would be combined in a cost-benefit analysis to determine the maximum allowable growth reduction before tending was economically and biologically feasible.

The implications for tending, using three different thresholds (20%, 30% and 40%), are compared in Table 3. All six plantations would require tending if the maximum allowable growth reduction was set at 20%. By increasing the threshold to 30%, however, only two plantations would require tending and at 40% only plantation # 1, which had an extremely high mean Shade Index value, would require tending. These differences could have a substantial impact on the number of plantations requiring tending and the funding level required to carry out these operations. Usually, tending dollars are limited for any given year, forcing a forest manager to set tending priorities. This ranking of plantations can be accomplished by using the difference between the measured index and critical index value (degree of severity). It can be assumed that the more

Table 3. Depiction of different tending options[1] based on different levels of acceptable growth reduction criteria.

Plantation #	Stock type	Soil texture	Mean shade index[2]	Critical Index Value[3] 40%	30%	20%
1	cont.	fine	65.22	62.21*	46.66*	31.11*
2	cont.	medium	39.25	61.17	45.88	30.59*
3	cont.	coarse	42.48	55.71	41.78*	27.85*
4	2+0	fine	40.45	55.18	41.39	27.59*
5	2+0	medium	45.79	64.44	48.33	32.22*
6	2+0	coarse	41.62	69.90	52.42	34.95*

[1] An asterisk following a critical index value denotes a "Yes" tending option.

[2] Mean Shade Index values are based on 60 samples per plantation.

[3] Critical index values were determined as the point of intersection between the appropriate regression line and three different levels of acceptable growth reduction from maximum potential (20 %, 30 % and 40 %).

the measured index value is greater than the critical index value, the more crucial it is that a release treatment be carried out. It should be understood, however, that due to the variability in seedling performance related to non-competitive parameters, the threshold value identified in Fig. 3 should probably be more realistically depicted as a "zone". Therefore, plantations whose Shade Index value fall within this zone would be evaluated further based on the experienced judgement of the forestry professional.

This program has the added advantage that by using CANOPY.GBA for pre- and post-herbicide assessment, the effectiveness of various release treatments can be quantified. Following treatment, the level of competition may visually be reduced, but if the competition level after release is not below the critical index value determined for a given site/stock type, the seedlings may not respond as expected.

Although the biological relationships used to develop the Shade Index are sound, limitations in using the CANOPY.GBA model as a "stand alone" quantitative decision-making tool should be identified. It has been recognized that it is difficult to confidently isolate the competition effects on seedling performance using retrospective analyses (Waller 1981). This effect often is confounded with the effects due to genetics, microsite (Cannell et al. 1984), size of planting stock (Mitchell et al. 1988), planting quality (Burdett et al. 1984), as well as chance factors. Therefore, it is suggested that a follow-up study be designed which systematically controls vegetation abundance around selected seedlings at pre-determined levels (treatments). The Shade Index (Eq. (4)), Total Canopy Cover (Eq. (1)), and other competition indices could be used to quantify the level of competition control within each treatment. The results from this type of study would better isolate the competitive influence on seedling performance and could be used to evaluate the operational suitability and reliability of various competition indices presented in the literature.

Using CANOPY.GBA as a regional index of competition may not be warranted since the regression equations used in the program were based on a limited sample size, especially with regards to geographic range. Therefore, the assumptions/relationships incorporated in the model should be validated and modified, if appropriate, to better reflect site heterogeneity on a regional scale. Another limitation with this study is that only four-year-old plantations were sampled. In northern Ontario, it is common to make tending decisions for plantations in this age-class. It cannot, however, be assumed that seedling responses to competition for individuals of different age-classes would be the same. Therefore, it would be useful to establish a time-series experiment designed to address this hypothesis. Finally, if precise estimates of seedling diameter are required

for growth and yield purposes, then additional variables should be included in the model. For example, stock quality, commonly expressed as the size of the stock at time of planting, has been found to greatly enhance the competitive tolerance of individual seedlings (Mitchell et al. 1988; Morris et al. 1990). As previously mentioned, other factors such as genetic, microsite, and planting quality may also interact to increase variability in seedling performance.

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